

APPLICATION FOR UNITED STATES LETTERS PATENT

FOR

TUNING FILTERS HAVING TRANSDUCTOR CELLS

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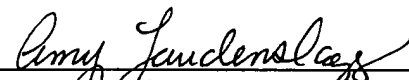
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"Express Mail" Mailing Label No. EV140153625US

Date of Deposit 01/13/2004

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TUNING FILTERS HAVING TRANSDUCTOR CELLS

BACKGROUND OF THE INVENTION

Field of the Invention

5 The present invention relates to electrical signal processing, and, in particular, to continuous-time filters implemented with transconductor cells, such as filters having one or more biquadratic filter sections and filters having ladder structures.

Description of the Related Art

10 Fig. 1 shows a block diagram of a prior-art filter **100** used to generate a filtered electrical output signal **106** from an electrical input signal **102**. Filter **100** has two biquadratic filter sections **104a** and **104b** and a tuning circuit **108**. Filter section **104a** receives and filters input signal **102**. Filter section **104b** receives and further filters the signal generated by filter section **104a** to generate output signal **106**. Tuning circuit **108** provides control signals **110** that control the tuning of filter sections **104a-b**.

15 Fig. 2 shows a block diagram of the architecture of each biquadratic filter section **104** of Fig. 1. As shown in Fig. 2, each biquadratic filter section **104** has four transconductor (g_m) cells **202a-d** (having transconductances g_{m1} , g_{m2} , $-g_{m3}$, and $-g_{m4}$, respectively) and two capacitors C1 and C2. The filter section's input signal V_{in} is received at the input to g_m cell **202a**, while the filter section's output signal V_{out} is presented at the node shared by g_m cells **202b** and **202d** and capacitor C2. The biquadratic filter section of Fig. 2 may be said to have an input node **204** (to which g_m cell **202a** is connected), an intermediate node **206** (to which capacitor C1 and all four g_m cells are connected), and an output node **208** (to which capacitor C2 and g_m cells **202b** and **202d** are connected).

Each biquadratic filter section **104** in Fig. 1 implements a pair of corresponding complex poles located in the complex plane at $A \pm Bj$, where the Q of the filter section is given by $\sqrt{A^2 + B^2} / 2A$.

25 Fig. 3 shows a schematic circuit diagram of the architecture of the main components of each transconductor cell **202** of Fig. 2. As shown in Fig. 2, the cell's differential input signal V_{in+} , V_{in-} is respectively applied to the gates of transistors M1 and M2. The outputs from current sources I1 and I2 are applied to the drains of M1 and M2, respectively, while the sources of M1 and M2 are both connected to the input of current sink I3. The cell's differential output signal V_{out+} , V_{out-} appears at the drains of M1 and M2. Common-mode control circuit **302** samples the differential output signal and generates a control signal **304** for current sink I3, e.g., to maintain a desired common-mode voltage level at V_{out+} and V_{out-} .

Referring again to Fig. 1, tuning circuit 108 of filter 100 has an oscillator 112 consisting of two integrators 114a and 114b configured in a loop, where each integrator 114 has a transconductor cell 116 and a capacitor 118. In addition, tuning circuit 108 has a reference oscillator 120, a phase detector 122, and a charge pump/filter 124. Phase detector 122 compares the reference oscillator's output signal 126 to a signal 128 based on the signal oscillating within oscillator 112 to generate UP or DOWN control signals for charge pump/filter 124, depending on whether the phase of oscillation signal 128 lags or leads the phase of reference signal 126. Charge pump/filter 124 accumulates electrical charge corresponding to the UP/DOWN signals from phase detector 122 to generate a tuning control signal 130 used to control the tuning of gm cells 116a-b to drive the oscillation frequency of oscillator 112 to match that of reference oscillator 120. As such, tuning circuit 108 functions as a phase-locked loop (PLL).

The electrical characteristics of transconductor cells 116a-b and capacitors 118a-b are specifically selected to replicate as closely as possible the electrical characteristics of each biquadratic filter section 104 in the main signal path of filter 100. As such, the same control signal (130) used to control the tuning of gm cells 116a-b in oscillator 112 is also applied as control signals 110 to control the tuning of gm cells in each biquadratic filter section 104 (as indicated in both Figs. 1 and 2).

Although not shown in the figures, an amplitude detector is often employed within tuning circuit 108 to monitor the amplitude of the signal oscillating within oscillator 112 to adjust the output conductance of each gm cell in order to maintain a constant, desired oscillator amplitude. This can provide accurate tuning of the Q of each biquadratic filter section 104 in filter 100.

Notwithstanding the general operability of filter 100, errors will typically result from a number of sources, including differences in parasitic capacitances at the transconductor cell output nodes, random component mismatch, and differences in cell loading. In addition, the reference oscillator in the tuning circuit can create interference with the signal being filtered in the main signal path.

SUMMARY OF THE INVENTION

Problems in the prior art are addressed in accordance with the principles of the present invention by providing, in one exemplary embodiment, circuitry comprising a filter having one or more filter sections, wherein at least one of the one or more filter sections comprises a plurality of transconductor (gm) cells. At least one of the gm cells can be configured to have substantially zero transconductance, such that the at least one filter section will oscillate.

BRIEF DESCRIPTION OF THE DRAWINGS

Other aspects, features, and advantages of the present invention will become more fully apparent from the following detailed description, the appended claims, and the accompanying drawings in which like reference numerals identify similar or identical elements.

5 Fig. 1 shows a block diagram of a prior-art filter having two biquadratic filter sections;

Fig. 2 shows a block diagram of the architecture of each biquadratic filter section of Fig. 1;

Fig. 3 shows a schematic circuit diagram of the architecture of each transconductor cell of Fig. 2;

Fig. 4 shows a block diagram of a filter having biquadratic filter sections, according to one embodiment of the present invention;

10 Fig. 5 shows a block diagram of the tuning circuit of Fig. 4;

Fig. 6 shows a schematic circuit diagram of the architecture of the main components of the third transconductor cell of the biquadratic filter section of the tuning circuit of Fig. 4;

Fig. 7 shows a filter having biquadratic filter sections, according to an alternative embodiment of the present invention;

15 Fig. 8(a) shows a block diagram of a filter having a ladder structure, according to one embodiment of the present invention; and

Fig. 8(b) shows a block diagram of a resonator of the filter of Fig. 8(a).

DETAILED DESCRIPTION

20 The appearances of the phrase "in one embodiment" in various places in the specification are not necessarily all referring to the same embodiment, nor are separate or alternative embodiments necessarily mutually exclusive of other embodiments.

Preferred embodiments of the present invention employ a technique for tuning filters implemented with transconductor cells, such as filters having biquadratic filter sections and filters having ladder structures. According to one embodiment of this technique, a biquadratic filter section is designed
25 to support both a filter mode (in which the section functions as a conventional filter) and a tuning mode (in which the section oscillates and can be tuned to achieve a desired cutoff frequency). In one application, a biquadratic filter section of the present invention is configured to operate as the tuning circuit for a filter having a main signal path with one or more instances of analogous biquadratic filter sections. In another application, each filter section in the main signal path of a filter is implemented
30 using an instance of a biquadratic filter section of the present invention including tuning circuitry that enables each filter section to tune itself. The present invention can also be implemented in the context of other types of filters implemented using transconductor cells, such as filters with ladder structures.

The present invention can provide filters having lower power dissipation, more accurate tuning, and reduced interference as compared with prior-art filters, such as those based on the architecture of Fig. 1.

Exemplary Filters having Biquadratic Filter Sections

Fig. 4 shows a block diagram of a filter 400, according to one embodiment of the present invention. Filter 400 has a main signal path comprising one or more biquadratic filter sections 404, where the main signal path receives an input signal 402 and generates the filtered output signal 406, where the output from each biquadratic filter section provides the input to the next biquadratic filter section along the main signal path. Each biquadratic filter section 404 has the same general architecture as that shown in Fig. 2. Filter 400 also has a tuning circuit 408, which provides tuning signals 410 to each biquadratic filter section 404 along the main signal path.

Fig. 5 shows a block diagram of tuning circuit 408 of Fig. 4. As shown in Fig. 5, tuning circuit 408 has, among other elements to be discussed later on, a biquadratic filter section 510, which also has the same general architecture as that shown in Fig. 2. In addition, with the sole exception of the third transconductor cell of biquadratic filter section 510 of tuning circuit 408 (corresponding to gm cell 202c of Fig. 2), each transconductor cell of each biquadratic filter section (i.e., section 510 of Fig. 5 and sections 404 of Fig. 4) in filter 400 has the same general architecture as that shown in Fig. 3.

Fig. 6 shows a schematic circuit diagram of the architecture of the main components of the third transconductor cell of biquadratic filter section 510 of tuning circuit 408 of Figs. 4 and 5. In addition to all of the elements shown in Fig. 3, this third gm cell has a set of switches 602 that can be selectively configured to apply either (a) the differential input signal V_{in+} , V_{in-} to the two gm cell inputs, respectively, or (b) the common-mode voltage signal V_{cm} to both gm cell inputs. When the differential input signal V_{in+} , V_{in-} is selected, the third transconductor cell operates in the same (i.e., filter mode) manner as the other third transconductor cells of the other biquadratic filter sections (i.e., sections 404). However, when the common-mode voltage signal V_{cm} is selected, biquadratic filter section 510 of tuning circuit 408 will oscillate at a frequency corresponding to the filter section's cutoff frequency when the filter section is operated in its filter mode.

This can be demonstrated mathematically. In particular, the transfer function for a biquadratic filter section having an architecture as shown in Fig. 2 is given by Equation (1) as follows:

$$\frac{V_{out}}{V_{in}} = \frac{g_{m1}}{g_{m4}} * \frac{\frac{g_{m2}g_{m4}}{C_1C_2}}{s^2 + s\frac{g_{m3}}{C_1} + \frac{g_{m2}g_{m4}}{C_1C_2}}, \quad (1)$$

where the cutoff frequency ω_0 and the Q of the biquadratic filter section are given by Equations (2) and (3) as follows:

$$\omega_0 = \sqrt{\frac{g_{m2}g_{m4}}{C_1C_2}} \quad (2)$$

$$Q = \sqrt{\frac{g_{m2}g_{m4}}{g_{m3}}} \sqrt{\frac{C_1}{C_2}}. \quad (3)$$

Referring again to Fig. 6, when the common-mode voltage signal V_{cm} is applied to the inputs of the third gm cell of biquadratic filter section 510, the transconductance g_{m3} of that third gm cell goes to zero, which, according to Equation (3) makes the Q of filter section 510 go to infinity. This effectively moves the poles of filter section 510 to the $j\omega$ j axis (as indicated by replacing the g_{m3} term in Equation (1) with 0), which in turn allows filter section 510 to oscillate and, in particular, to oscillate at the cutoff frequency ω_0 . Note that, although the transconductance of the third gm cell is set to zero for the oscillation mode, the loading at all nodes of filter section 510 is approximately the same as when the third gm cell is operated in its filter mode.

Referring again to Fig. 5, in addition to biquadratic filter section 510, tuning circuit 408 has components that assist in the generation of tuning control signals 410 of Fig. 4. For example, programmable controller 502 loads timer 504, counter 506, and tuning control block 508 with appropriate address and data information and implements a tuning algorithm. In particular, programmable controller 502 applies oscillate control signal 516 and tuning vector 518 to biquadratic filter section 510 and receives borrow signal 520 from counter 506. Depending on the implementation, tuning vector 518 controls such characteristics as transconductance, capacitance, and source degeneration to adjust the frequency of oscillation of biquadratic filter section 510. Although not shown in Fig. 5, control signals

410 of Fig. 4 are identical to tuning vector 518 or at least are generated based on some or all of the information represented in tuning vector 518.

When dictated by controller 502, tuning control block 508 applies oscillate control signal 516 to biquadratic filter section 510 to control switches 602 in the third gm cell (see Fig. 6) to select the common-mode voltage signal V_{cm} to cause filter section 510 to oscillate. The output of biquadratic filter section 510 is sliced at comparator 512, whose output is applied to gate 512 along with the output from timer 504 to generate the input to counter 506. Timer 504 is set to a desired measurement period, while counter 506 is preset to the target number of oscillation cycles for the desired filter cutoff frequency ω_0 that should occur during the measurement period. If, at the end of the timer period, a borrow has occurred, then there were more oscillation cycles than desired, and controller 502 adjusts the tuning vector to a lower value. If no borrow occurs, then controller 502 adjusts the tuning vector to a higher value. In this way, programmable controller 502 ensures that biquadratic filter section 510 will oscillate at the desired cutoff frequency ω_0 . In addition, Q tuning can be accomplished by adjusting the output conductance of the gm cells within filter section 510 to achieve a desired oscillation amplitude.

In a preferred implementation, tuning vector 518 represents a set of digital control signals that can be stored in flip-flop circuitry within tuning control block 508. As such, the tuning of biquadratic filter section 510 can be implemented intermittently as opposed to the continuous tuning of prior-art filter 100 of Fig. 1. This can reduce the power consumption of filter 400 of the present invention as compared to that of prior-art filter 100. In addition, filters of the present invention can avoid having to implement the reference generator and phase-locked loop of prior-art filter 100.

Because biquadratic filter section 510 of Fig. 5 (preferably) has the same general architecture as each biquadratic filter section 404 in the main signal path of filter 400 of Fig. 4, filter section 510 can be -- and preferably is -- implemented as a replica that more closely matches the filter sections in the main signal path than can be achieved using oscillator 112 of prior-art filter 100 of Fig. 1. As such, the errors associated with such sources as differences in parasitic capacitances at the transconductor cell output nodes, random component mismatch, and differences in cell loading can be reduced.

Fig. 7 shows a filter 700, according to an alternative embodiment of the present invention. As shown in Fig. 7, and like filter 400 of Fig. 4, filter 700 has a main signal path comprising one or more biquadratic filter sections 704, where the main signal path receives an input signal 702 and generates the filtered output signal 706, where the output from each biquadratic filter section provides the input to the next biquadratic filter section along the main signal path. Like filter 400, each section 704 in filter 700 has a biquadratic filter having the same general architecture as that shown in Fig. 2. Unlike filter 400,

however, filter 700 does not have a separate tuning circuit outside of the main signal path. Rather, in filter 700, each section 700 is itself an instance of tuning circuit 408 having tuning elements as shown in Fig. 5 and a biquadratic filter section 510, whose third gm cell is shown in Fig. 6.

In this embodiment, each quadratic filter section 704 can tune itself without having to rely on any replica. Moreover, each filter section 704 can be implemented to perform its tuning algorithm independent of each other filter section 704. Since each filter section 704 is able to store its own tuning vector, depending on the particular application, the tuning of different filter sections can be selected to be either simultaneous or staggered in time, whichever is more desirable in terms of minimizing the impact to normal filtering operations.

Exemplary Filters having Ladder Structures

In the previous section, the present invention was described in the context of filters having one or more biquadratic filter sections in the filter's main signal path. In this section, the present invention is described in the context of filters having a ladder structure.

Fig. 8(a) shows a block diagram of a filter 800 having a ladder structure, according to one embodiment of the present invention. Fig. 8(b) shows a block diagram of resonator RES no. 1 of filter 800. According to this embodiment, transconductor cell g_{md} of Fig. 8(b) is implemented using the same gm cell architecture as shown in Fig. 6. Filter 800 can be configured as an oscillator by switching off transconductor cell g_{md} of Fig. 8(b) (i.e., by configuring switches 602 of Fig. 6 such that the common-mode voltage signal V_{cm} is applied to both gm cell inputs).

In one implementation, filter 800 can be used in place of biquadratic filter section 510 of Fig. 5 to form a ladder tuning circuit that is analogous to biquadratic tuning circuit 408 of Fig. 4. In a configuration analogous to that shown for filter 400 of Fig. 4, this ladder tuning circuit can be used to tune the main signal path of a filter having a ladder structure such as that shown in Fig. 8(a).

Alternatively, in a configuration analogous to that shown for filter 700 of Fig. 7, this ladder tuning circuit can be part of the ladder filter's main signal path.

The present invention has been described in the context of filters having biquadratic filter sections and filters having ladder structures. Both of these types of filters are implemented using transconductor cells. The present invention can be extended to apply to other suitable types of filters that are implemented using transconductor cells.

The present invention may be implemented as circuit-based processes, including possible implementation as a single integrated circuit (such as an ASIC or an FPGA), a multi-chip module, a single card, or a multi-card circuit pack. As would be apparent to one skilled in the art, various functions

of circuit elements may also be implemented as processing steps in a software program. Such software may be employed in, for example, a digital signal processor, micro-controller, or general-purpose computer.

5 It will be further understood that various changes in the details, materials, and arrangements of the parts which have been described and illustrated in order to explain the nature of this invention may be made by those skilled in the art without departing from the scope of the invention as expressed in the following claims.